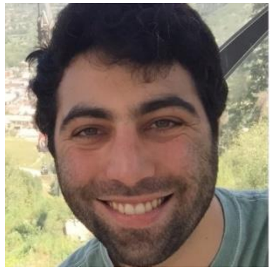
Identifying mechanisms of quantum nematic transitions from the dynamic susceptibility

CORRELATED ELECTRON SYSTEMS – NOVEL DEVELOPMENTS

FTPI – MAY 2018

AK, SAMUEL LEDERER, DEBANJAN CHOWDHURY, EREZ BERG, ANDREY CHUBUKOV

ARXIV:1708.05308, ARXIV:1711.03984

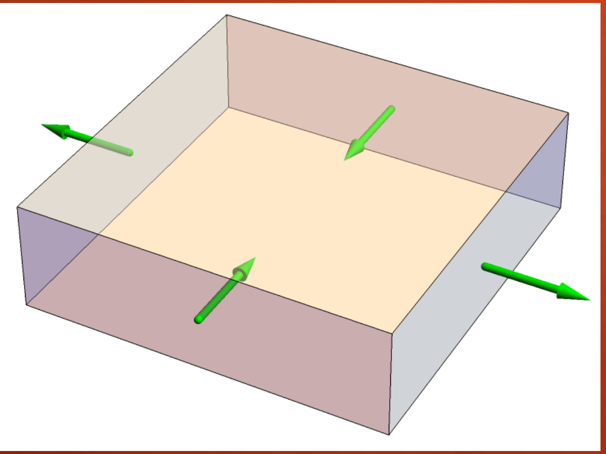


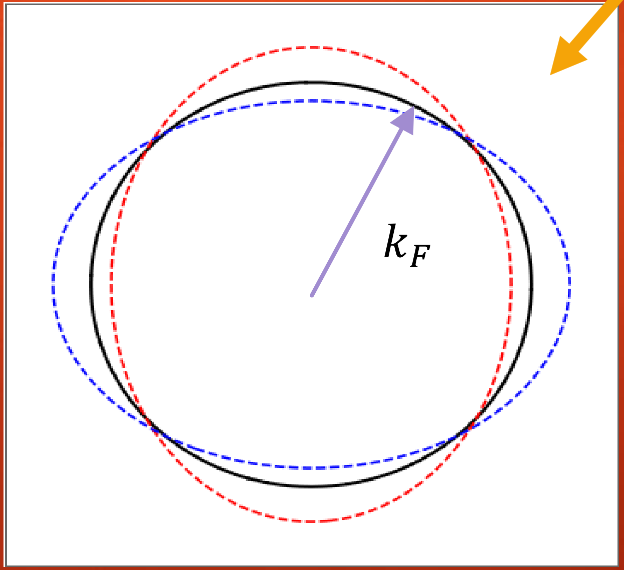

Background

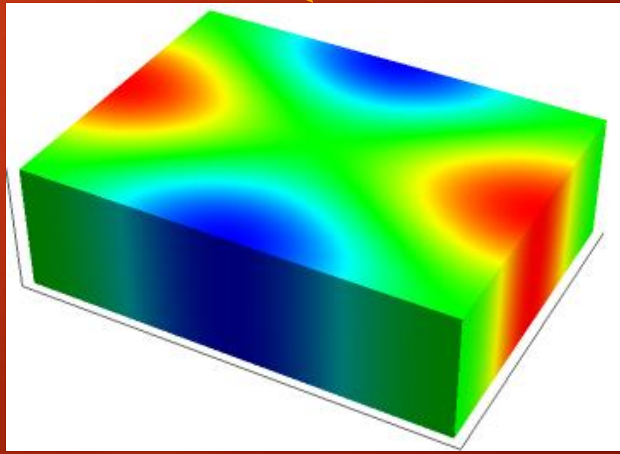
- Electronic nematicity
  - Quadruple deformation
  - Elliptic Fermi surface

Long wavelength
$Q = 0$

Anisotropic



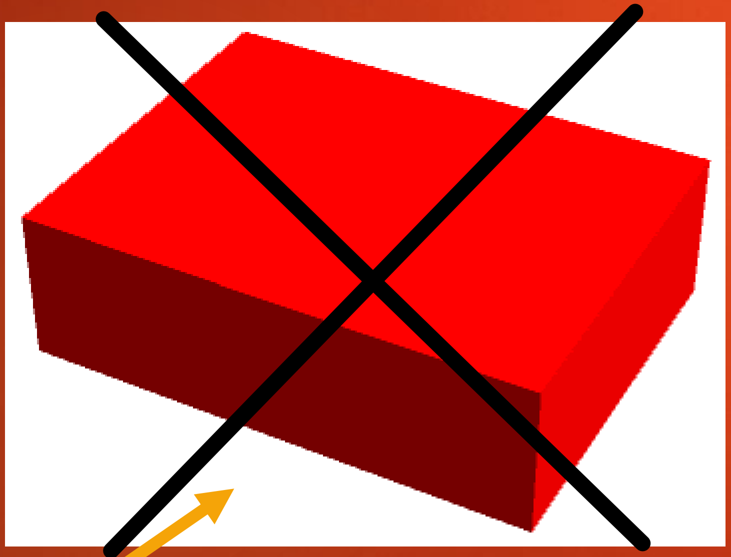


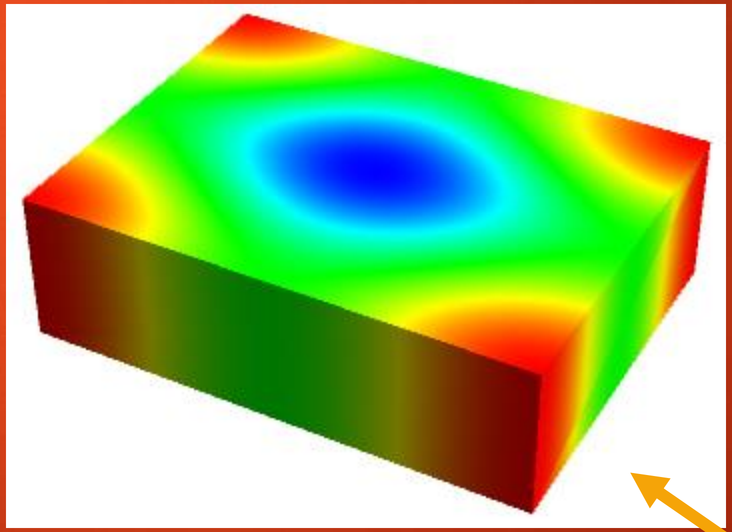


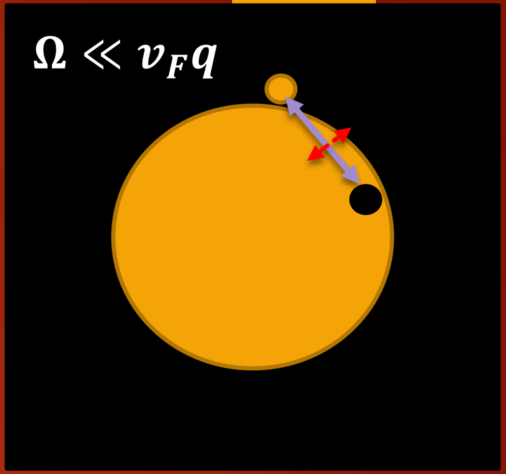
Background

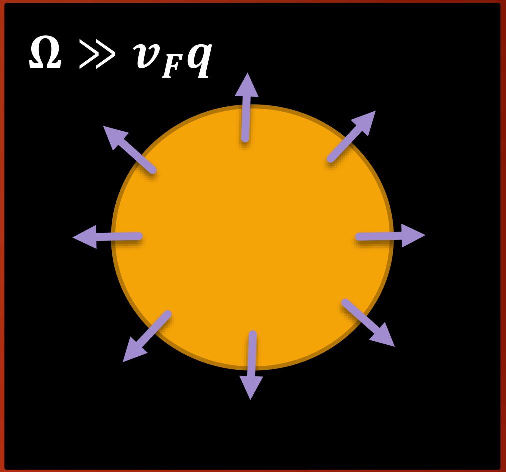
- Interacting electrons have two distinct regimes:

$$v_F q \gg \Omega \text{ and } v_F q \ll \Omega$$









Conserved order parameter

New regime to study!

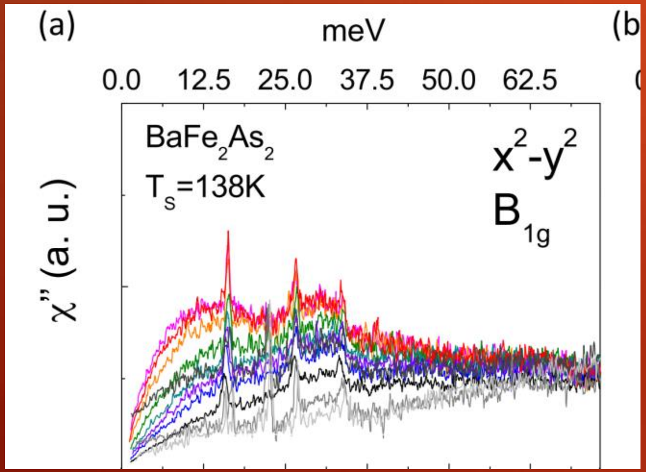
Nonconserved order parameter

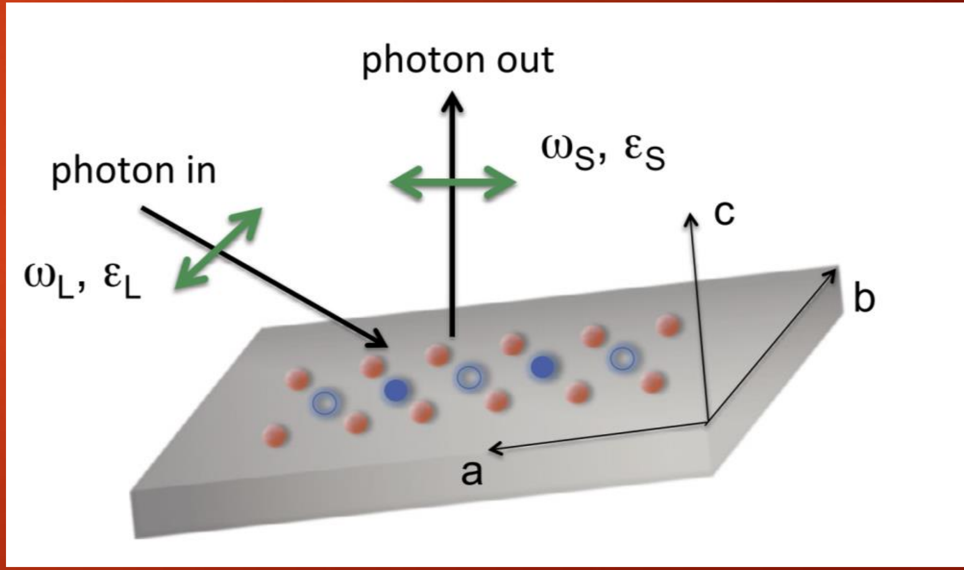
Background

- Polarization resolved Raman scattering
  - Strongly correlated materials (Fe-based superconductors)

- Optical measurement: $\Omega \gg v_F q$
  - Measures electronic density fluctuations:

$$I(\Omega) \propto \chi''_{l=2}(\Omega)$$

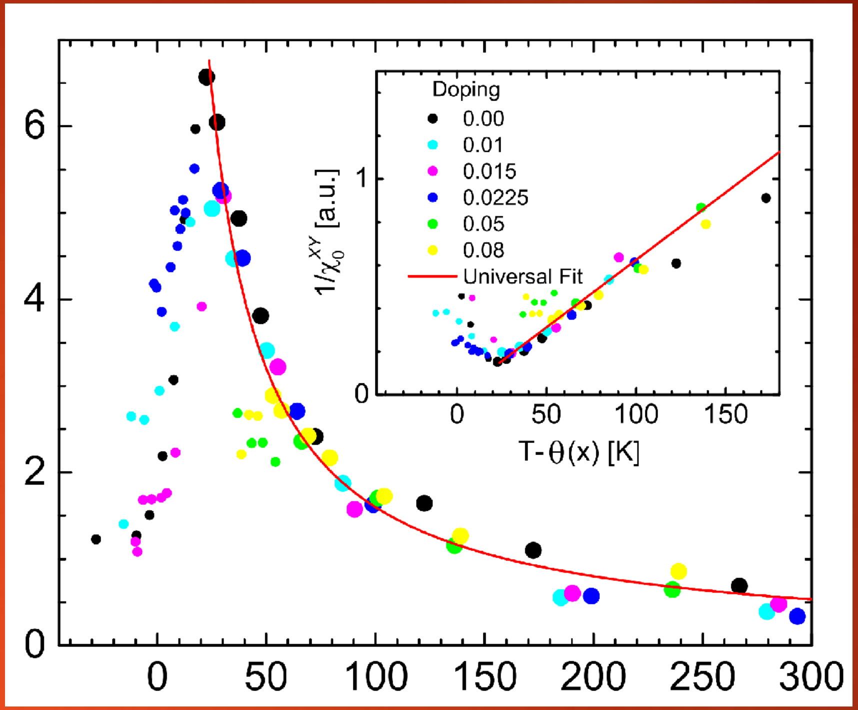




Y. Gallais, I. Paul 2016

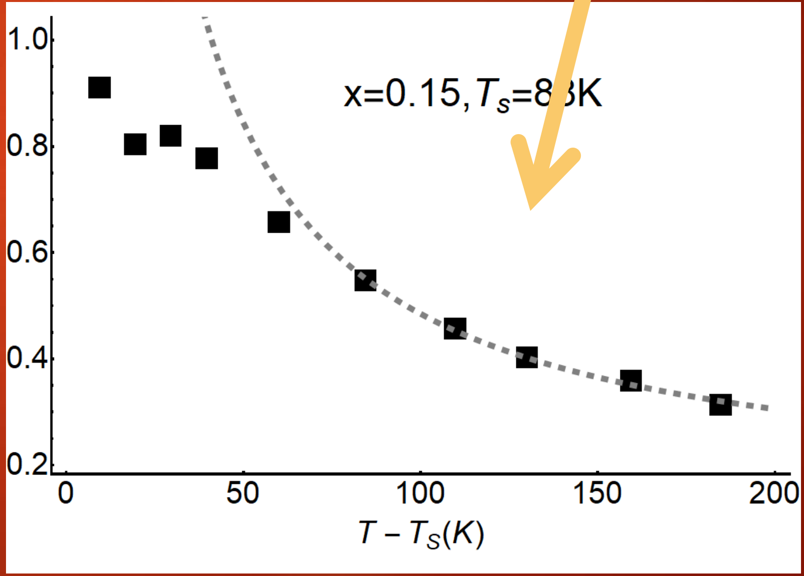
Background

- Raman studies of $FeSe_{1-x}S_x$
  - Many other materials as well



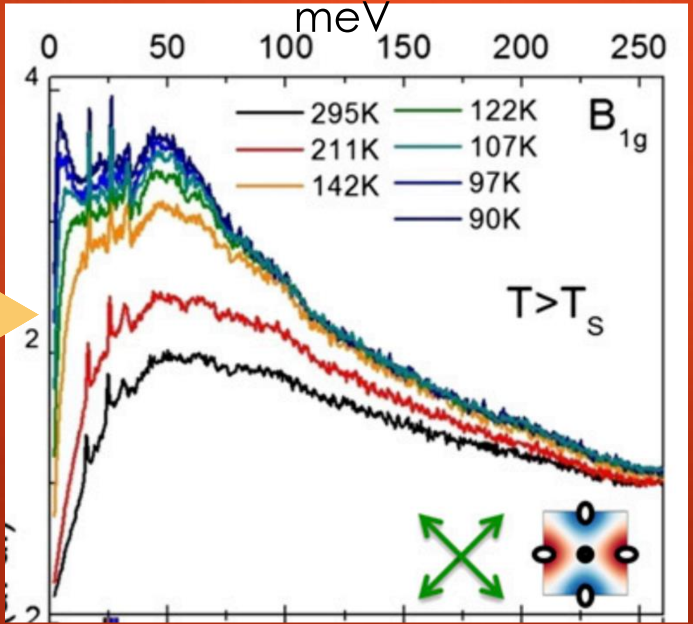
V Thorsmolle et. al. 2016

$\chi'(0)$



W.-L. Zhang et. al. (private/2017)

$\chi''(\Omega)$



P Massat et. al. 2016

Outline

- Model and central results
- $FeSe_{1-x}S_x$ Raman highlights
- Theory highlights
- Summary

Model

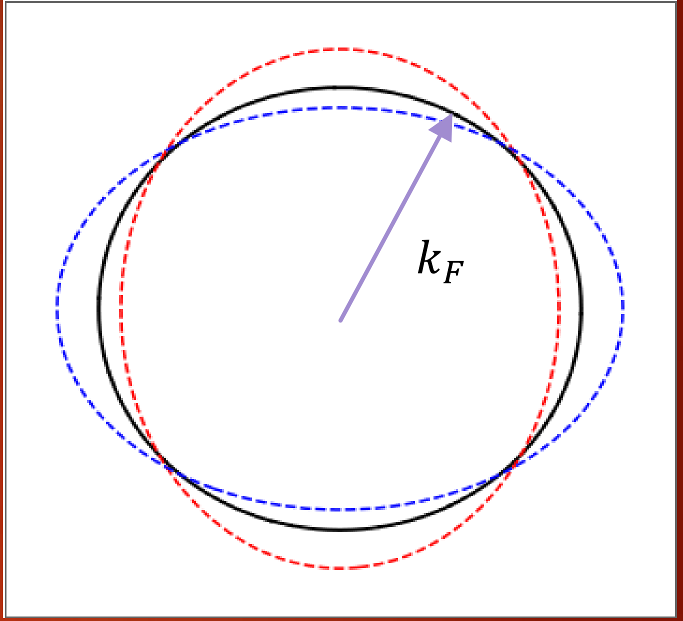
- 2D fermions + nematic boson
- Hamiltonian:

$$H_I = g \sum_{\mathbf{k},\mathbf{q}} \phi(\mathbf{q}) \psi^+\left(\mathbf{k}+\frac{\mathbf{q}}{2}\right) \psi\left(\mathbf{k}-\frac{\mathbf{q}}{2}\right) f(\mathbf{k})$$

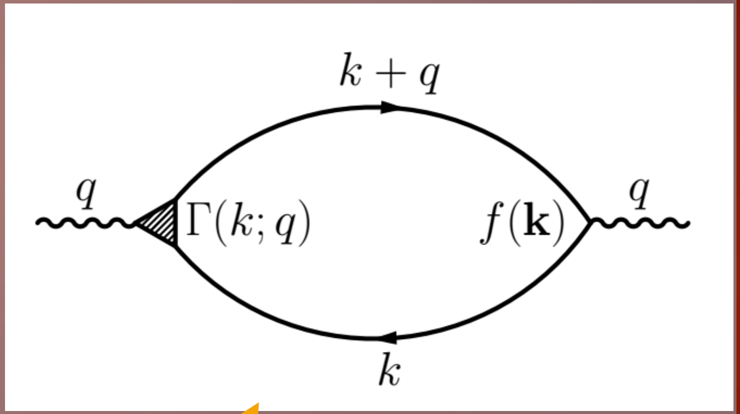
$$f(k) \approx f(\phi_k) = \cos(2\phi_k)$$

- Boson critical dynamics:

$$\chi(\mathbf{q}, \Omega_m \ll v_F q) = \frac{\chi_0}{\xi^{-2} + q^2 + \gamma \frac{|\Omega_m|}{v_F q} f^2(\phi_q)}$$



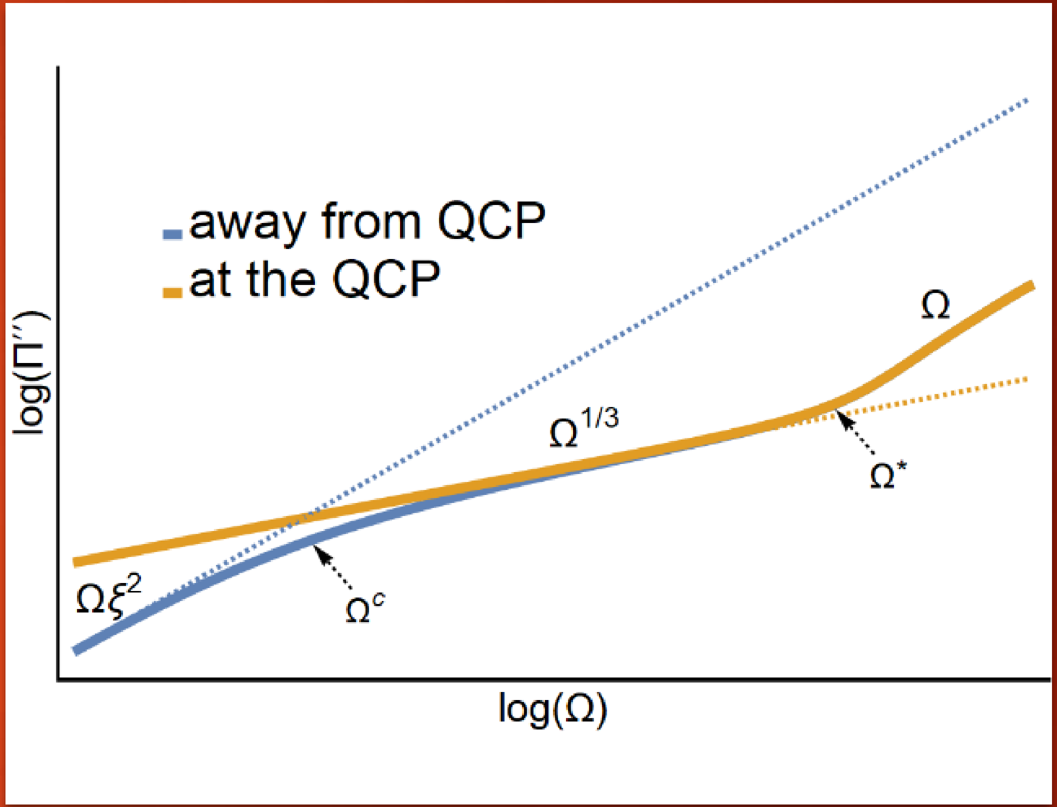
OUR GOAL

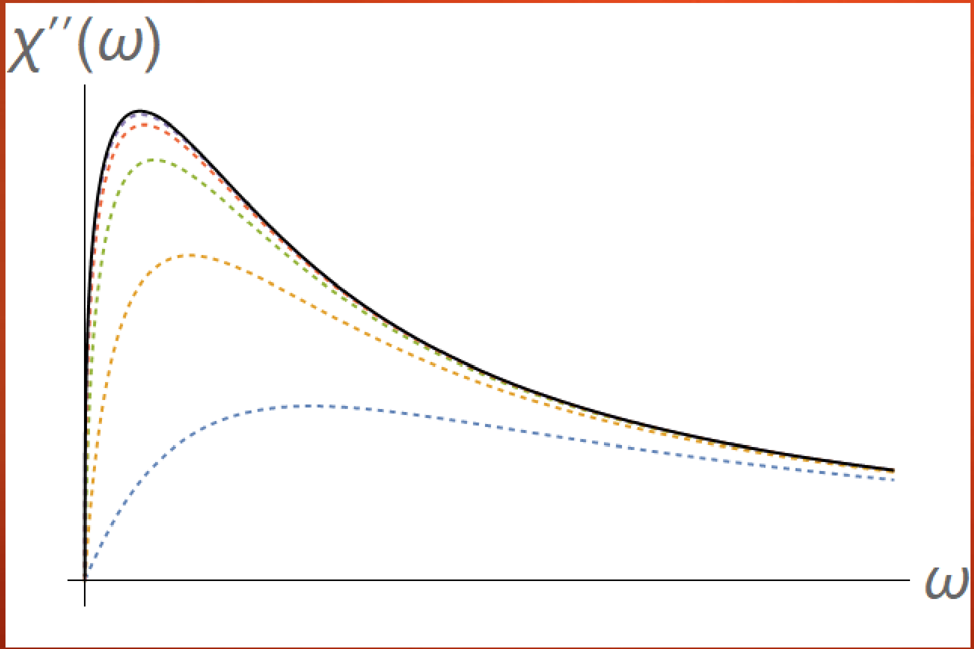


$$\Pi(\mathbf{q}=0, \Omega_m)$$

Results

- Result #1: form of $\Pi(q = 0, \Omega)$:
  - $$\Pi(\Omega_{\mathrm{m}}) \sim \Pi_0(\xi^{-1}) + \begin{cases} \Omega_{\mathrm{m}}\xi^2 & \Omega \ll \Omega^c \sim \xi^{-3} \\ \Omega_{\mathrm{m}}^{1/3} & \Omega \gg \Omega^c \end{cases}$$

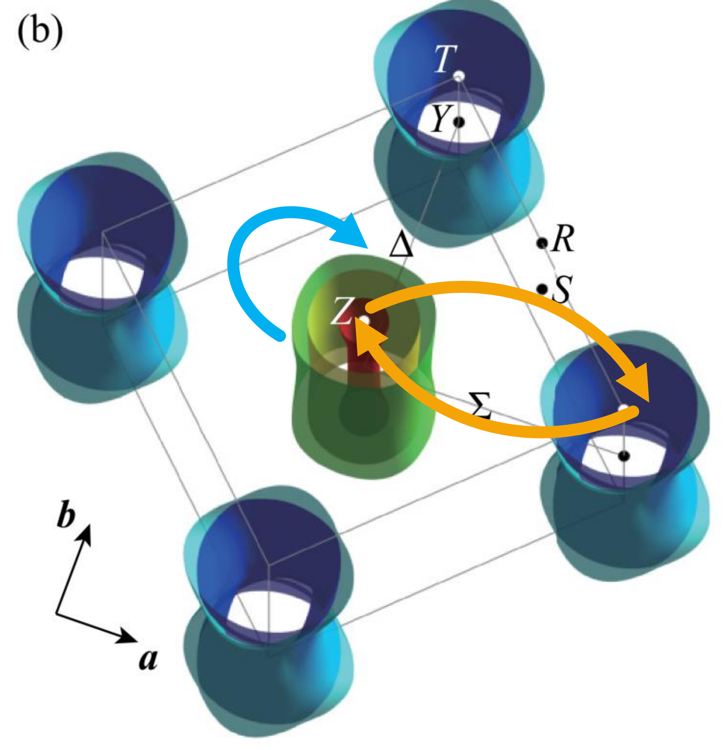




Results

- Result #2: identifying mechanisms of nematicity

FeSe DFT (Terashima et al 2014)



Pomeranchuk	Independent
Orbital (charge)	Composite magnetism
	Phonons
	…

Results

- Result #2: identifying mechanisms of nematicity

	Pomeranchuk	**Independent**
Critical scales	ξ	ξ_0, ξ
Amplitude $\chi(q \to 0, \Omega = 0)$	$\chi_0 \xi^2$	$\chi_0 \xi^2$
Amplitude $\chi(\mathrm{q} = 0, \Omega \to 0)$	Π_0	$\chi_0 \xi_0^2$
Slope $\chi''(\Omega)/\Omega$	$\propto \xi^2$	$\propto \xi^2 \xi_0^4$

Results

- Result #2: identifying mechanisms of nematicity

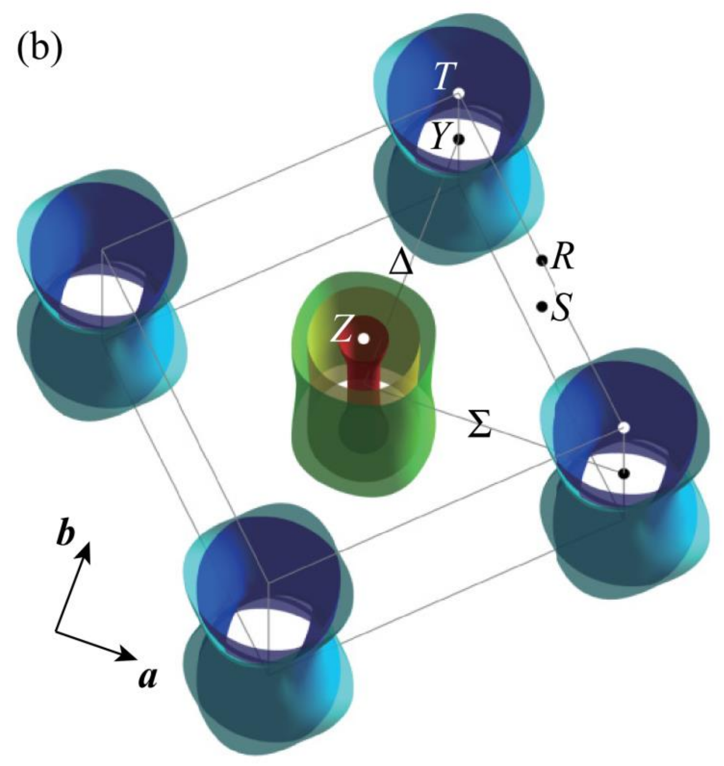
Pomeranchuk	Independent
$\chi_{pom} = \dfrac{\Pi}{1 - \bar{g}\Pi}$	$\chi_{ind} = \dfrac{\chi_0}{\xi_0^{-2} - \bar{g}'\Pi}$
$\xi^{-2} = \xi^{-2}$	$\xi^{-2} = \xi_0^{-2} - \bar{g}'\Pi_0$

Large for $\Omega \ll v_F q$ only!

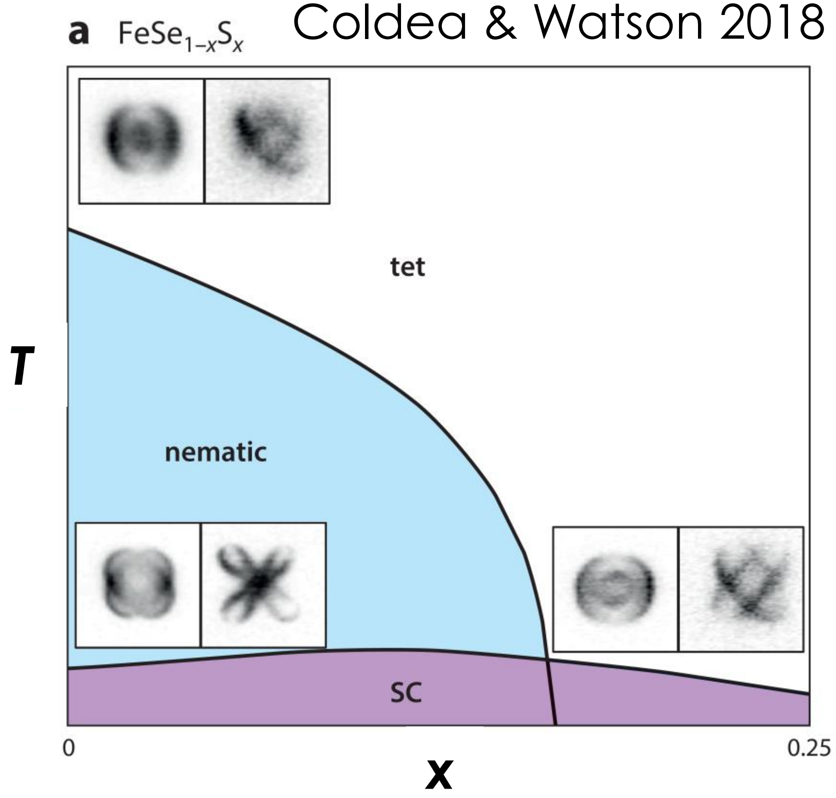
$FeSe_{1-x}S_x$ analysis highlights

- Some background on FeSe:

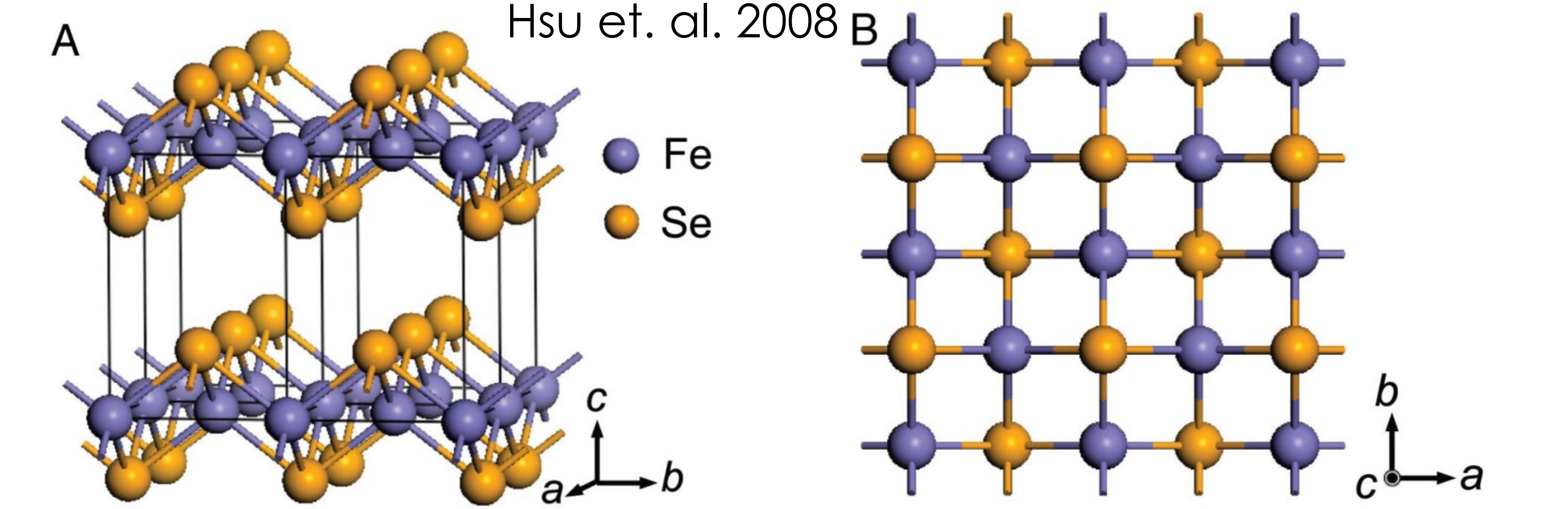
DFT (Terashima et al 2014)



Coldea & Watson 2018

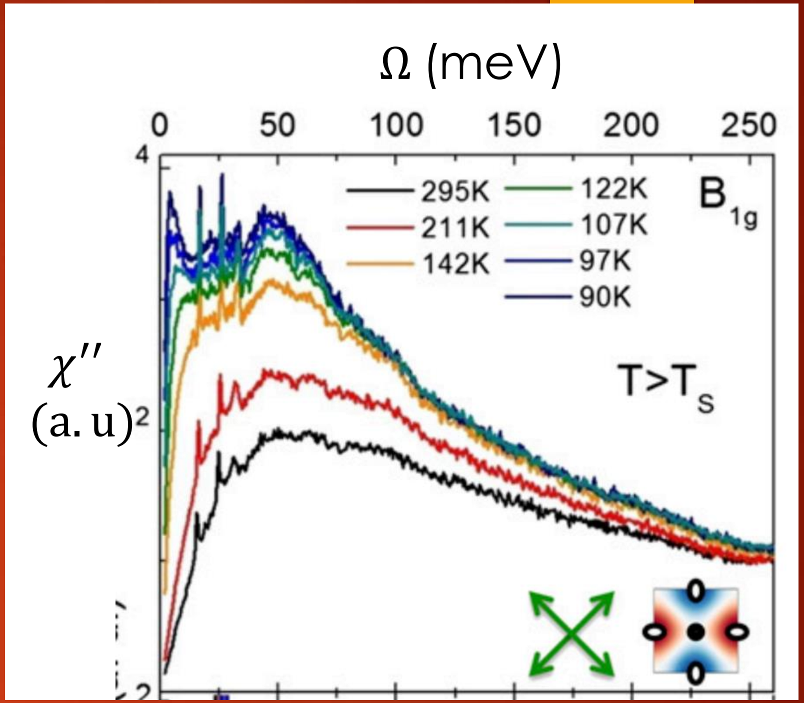


Hsu et. al. 2008

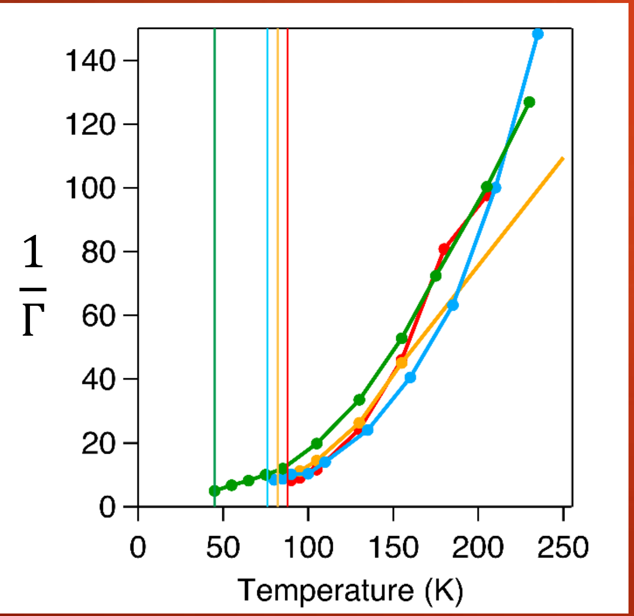


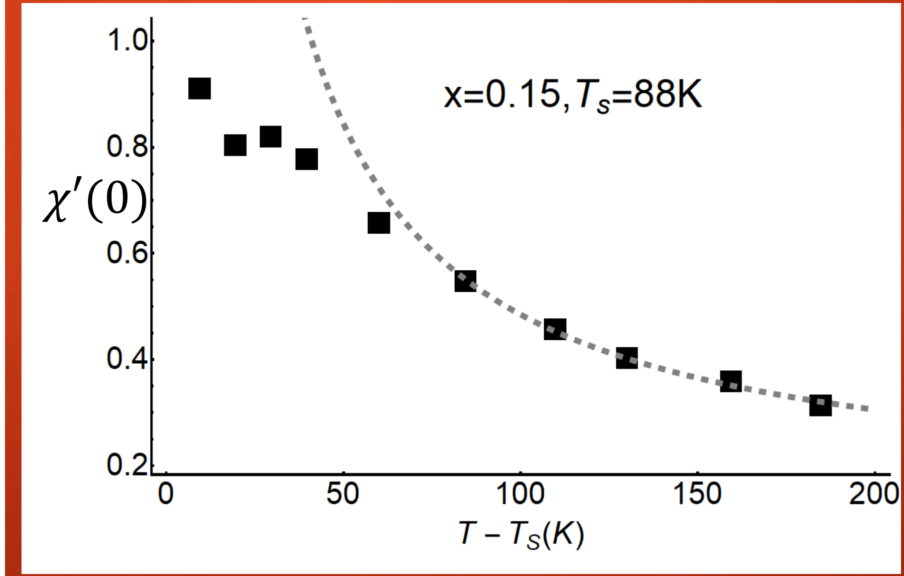
FeSe$_{1-x}$S$_x$ analysis highlights

- Raman studies on FeSe$_{1-x}$S$_x$:
  - Slope: $\Gamma = \chi''(\Omega \to 0)/\Omega$
  - Amplitude: $\chi'(0) \sim \int \frac{\chi''(\Omega)}{\Omega} d\Omega$



P Massat et. al. 2016





W.-L. Zhang et. al. (private/2017)

$FeSe_{1-x}S_x$ analysis highlights

- Comparison with theory (Pomeranchuk):

$$\chi'(0) = \Pi_0\left(1 - \frac{\arctan(k_F\xi)}{\mathrm{k_F}\xi}\right) = \Pi_0\left(1 - \frac{\pi}{2\mathrm{k_F}\xi} + \cdots\right)$$

$$\delta\chi' = \chi'_{\xi\to\infty}(0) - \chi'_{\xi}(0) \propto \xi^{-1}$$

$$\Gamma = \frac{\chi''(\Omega \to 0)}{\Omega} \propto \xi^2$$

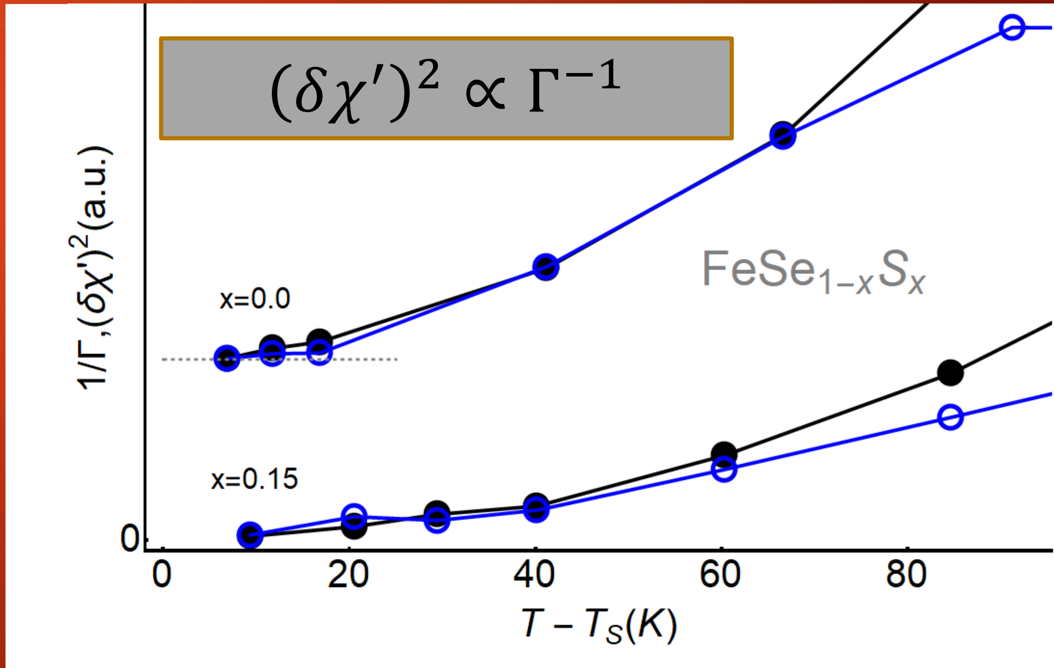
$FeSe_{1-x}S_x$ analysis highlights

- Comparison with theory (Pomeranchuk):

$$\chi'(0) = \Pi_0\left(1 - \frac{\arctan(k_F\xi)}{k_F\xi}\right) = \Pi_0\left(1 - \frac{\pi}{2k_F\xi} + \cdots\right)$$

$$\delta\chi' = \chi'_{\xi\to\infty}(0) - \chi'_{\xi}(0) \propto \xi^{-1}$$

$$\Gamma = \frac{\chi''(\Omega\to 0)}{\Omega} \propto \xi^2$$



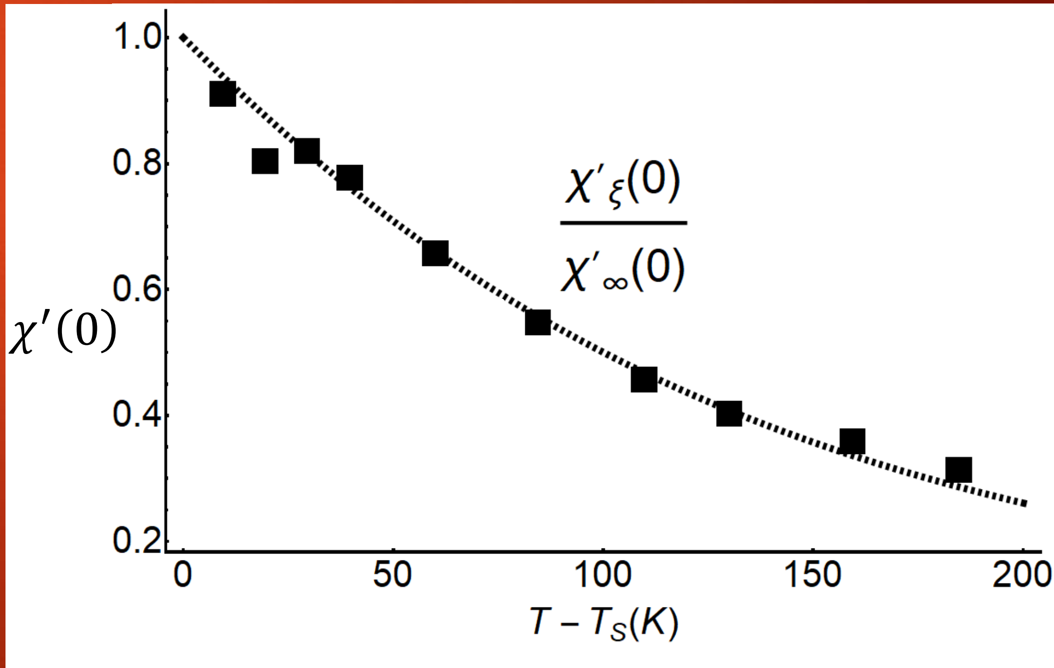
$FeSe_{1-x}S_x$ analysis highlights

- Comparison with theory (Pomeranchuk):

$$\chi'(0) = \Pi_0\left(1 - \frac{\arctan(k_F\xi)}{k_F\xi}\right) = \Pi_0\left(1 - \frac{\pi}{2k_F\xi} + \cdots\right)$$

$$\delta\chi' = \chi'_{\xi\to\infty}(0) - \chi'_{\xi}(0) \propto \xi^{-1}$$

$$\Gamma = \frac{\chi''(\Omega\to 0)}{\Omega} \propto \xi^2$$



What about pnictides?

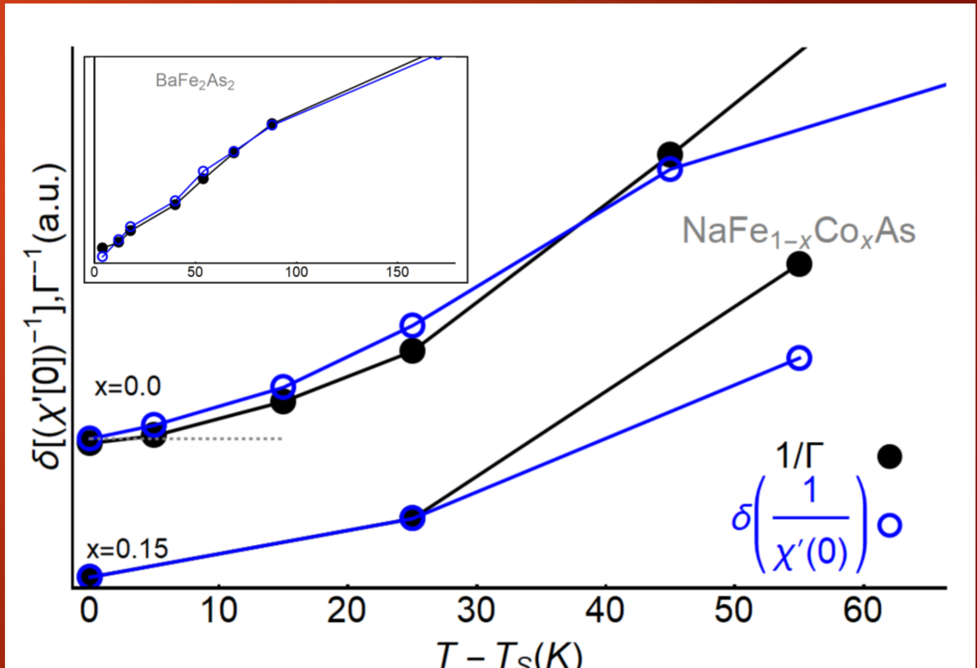
Other theories, e.g.:
Y Gallais, I Paul 2016
A Baum et. al. 2018
M Khodas, A Levchenko 2015

- 'Independent' scenario:

$$\delta\chi' \propto \xi^{-2}\xi_0^2 \qquad \delta\left(\frac{1}{\chi'}\right) \propto \xi^{-2} \qquad \Gamma^{-1} \propto \xi^{-2}\xi_0^{-4}$$

- Assuming constant ξ_0,

$$\delta\chi' \sim \delta\left(\frac{1}{\chi'}\right) \sim \Gamma^{-1}$$



Theory highlights

- Reminder:
  - Fermions coupled to QC boson

$$H_I = g \sum_{\mathbf{k},\mathbf{q}} \phi(\mathbf{q}) \psi^+ \left(\mathbf{k} + \frac{\mathbf{q}}{2}\right) \psi \left(\mathbf{k} - \frac{\mathbf{q}}{2}\right) f(\mathbf{k})$$

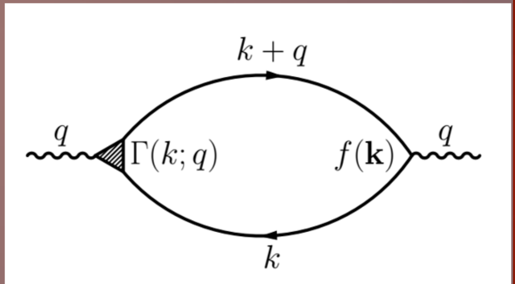
$$f(k) \approx f(\phi_k) = \cos(2\phi_k)$$

- Energy scales (at QCP):

Onset of Landau Damping (critical boson)	Onset of NFL (critical fermion)
$\omega_1 \propto \sqrt{\overline{g}\epsilon_F}$	$\omega_0 \propto \frac{\overline{g}^2}{\epsilon_F}$

$$\omega_0 \ll \omega_1$$

OUR GOAL

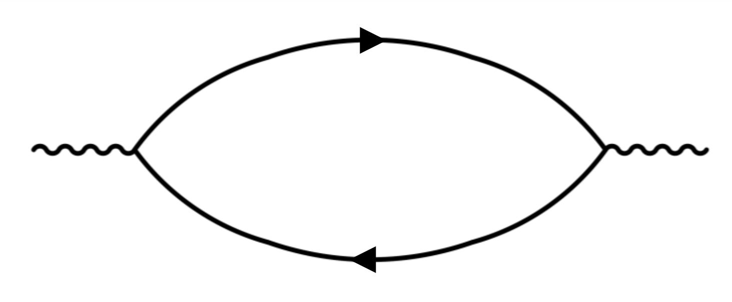


$$\Pi(\mathbf{q} = 0, \Omega_m)$$

Altshuler, Ioffe, Millis; …

Theory highlights

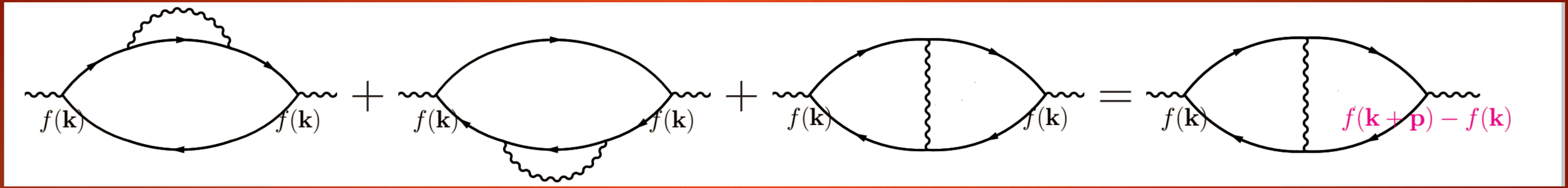
- Free fermion susceptibility:

 $= 0$

Free fermions $\Leftrightarrow$ all k – states are conserved!

Theory highlights

- Next order ($\omega_0 \ll \Omega \ll \omega_1$):



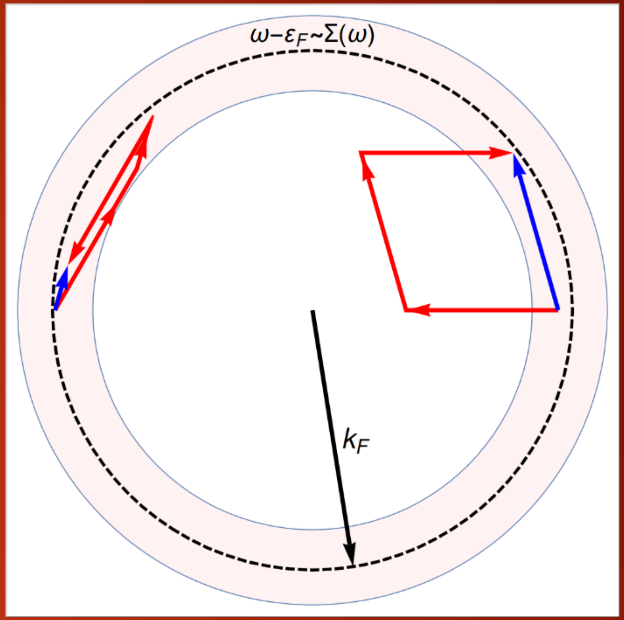
Breaks down for $\Omega < \omega_0$ (NFL regime)

Theory highlights

- Eliashberg theory ($\Omega_m \ll \omega_0$):
  - Most singular contributions:

$$\chi_{eff}(\Omega_m) \sim \frac{1}{q} \sim \frac{1}{\Omega_m^{1/3}}$$

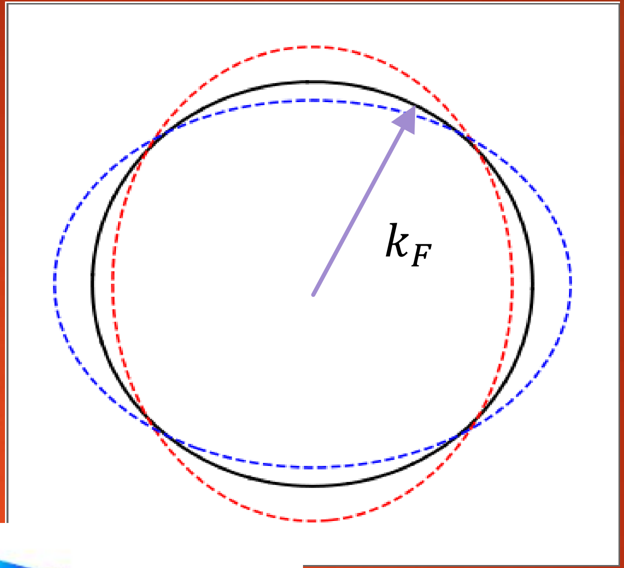
$$\boxed{\begin{array}{l} q \sim \Omega_m^{\frac{1}{3}} \ll k_F \\ \Sigma(\omega_m) \sim \omega_m^{\frac{2}{3}} \ll q \end{array}}$$

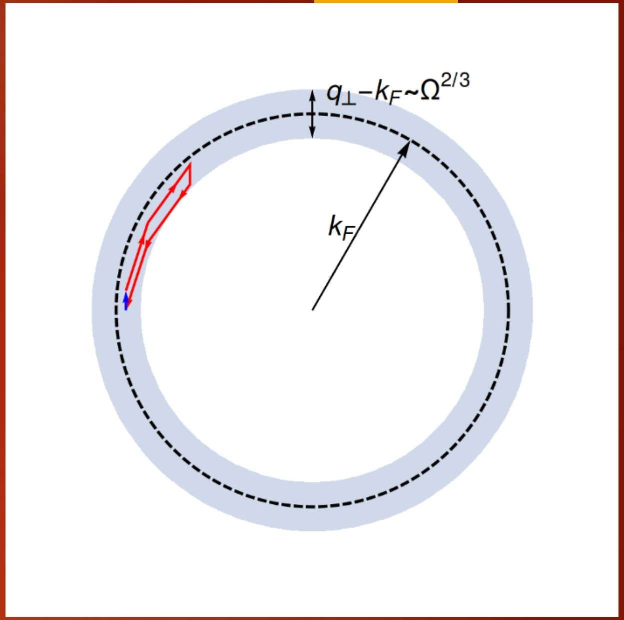


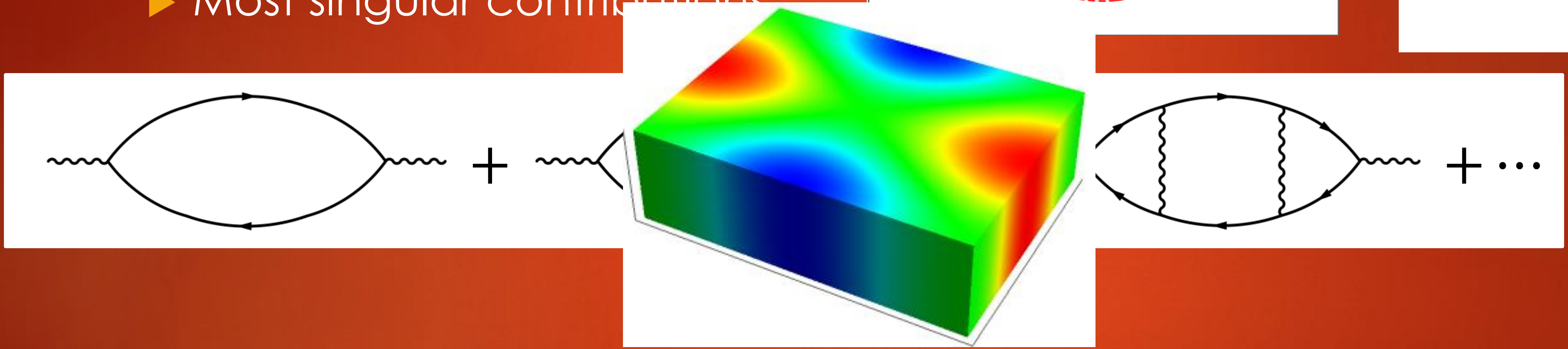
$$\chi = \frac{\chi_0}{q^2 + \gamma \frac{|\Omega_m|}{v_F q} f^2(\phi_q)}$$

Theory highlights

- Eliashberg theory ($\Omega_m \ll \omega_0$):
  - Most singular contributions:



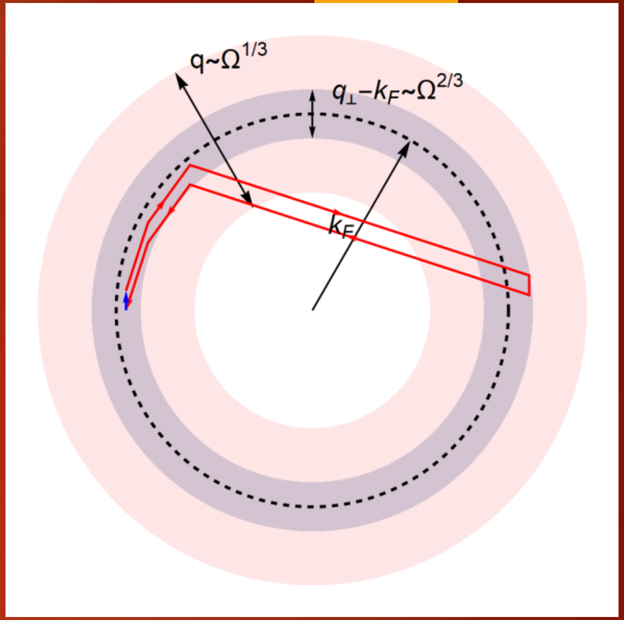




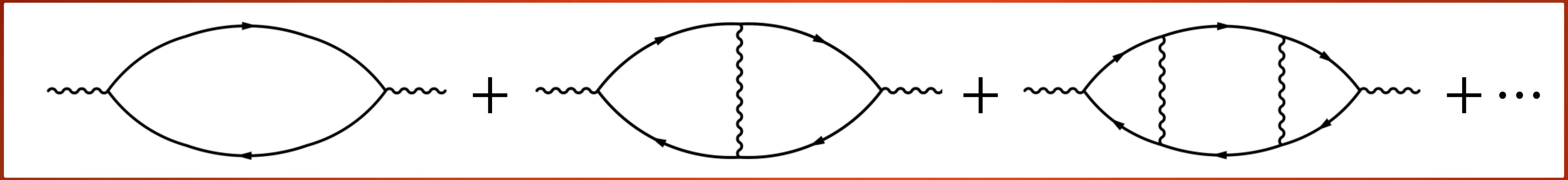
$= 0$

Small $q \sim 0$ – still conservation law!

Theory highlights

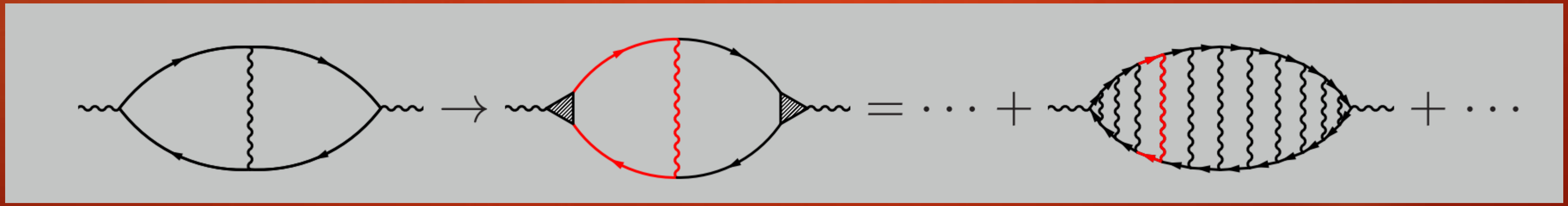


- Eliashberg theory ($\Omega_m \ll \omega_0$):
  - Most singular contributions:

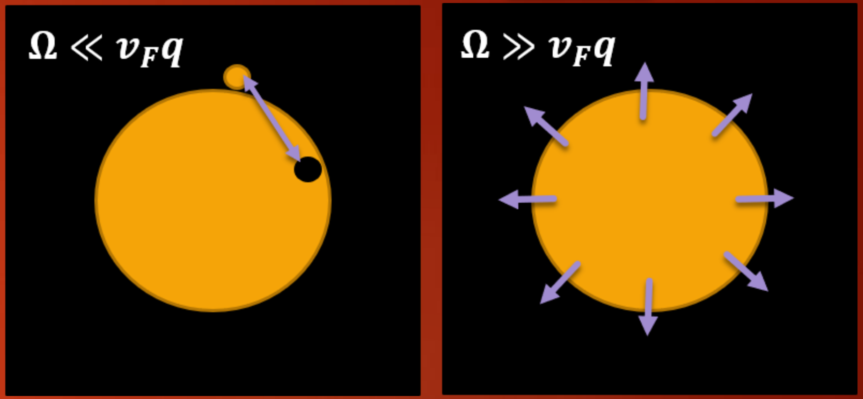


$= 0$

  - Large k correction:



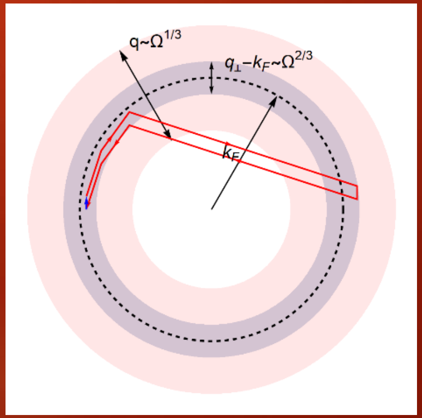
Summary



- Nonconserved order parameter
  - 'new' regime to study: $\Omega > 0, q = 0$
- Can identify driving mechanism
  - $\delta\chi' \sim \Gamma^{-1}$ vs $\delta\chi'^2 \sim \Gamma^{-1}$
  - FeSe – good agreement with Pomeranchuk scenario

Pomeranchuk	Independent
ξ	ξ_0, ξ

- Interplay between conservation laws and strong fluctuations
  - Singular fluctuations interfere destructively
  - No divergences: $\chi'' \propto \xi^2\Omega, \Omega^{\frac{1}{3}}$



Thank you!